

Hydrogeological assessment of a deep-seated coastal landslide based on a multi-disciplinary approach (Villerville, Normandy)

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Study area and issues



Located in the Pays d'Auge (Normandy), the Cirque des Graves is a rotationaltranslational landslide (Fig. 1) with multiple nested slip surfaces. It has an area of 47 hectares (450 m width x 1,600 m length). From top to bottom, the stratigraphy is **composed by 5 layers** : (i) Cenomanian chalk and glauconite; (ii) Albian clay and sands; (iii) Kimmeridgian clays & marls; (iv) Oxfordian marls; and (v) Upper-oxfordian sandstone (Fig. 3).

This landslide is characterized by :

- A continuous spreading due to local readjustments (2 to 10 cm.yr);
- Intermittent accelerations (*Fig. 2*) with retrogressive dynamics (e.g. 1982, 1989, 1995 & 2001);



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Outcrop of **numerous** springs in the central zone throughout the year (continental discharge ?);

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- Increase of conductivity (Fig. 7A) spatially (upstream to downstream) and temporally (autumn to spring);
- Significant increase of the global flow in spring : 109.75 to 172.47 l.mn⁻¹ at the slope scale (*Fig. 7B*) ;
- Possible **deeper and older**



Géosciences pour une Terre durabl

Fig. 1 - A: Location of the study field in Normandy; B: Morphological sketch of the four major coastal landsides of the Pays d'Auge, between Deauville and Honfleur. 1. Border of the Plateau d'Auge; 2. Main scarp of the landslides; 3. Secondary scarp; 4. Basal scarp; 5. Bumpy morphology; 6. Solifluction lobes morphology; 7. Spot height; 8. Temporary river flow; 9. Permanent river flow; 10. Municipality boundary.

The purposes of this study are :

- (1) Improve the **general hydrogeological knowledge** on the landslide functioning ;
- (2) Determine the **main water paths** at the slope scale;
- (3) Identify the major discharge areas of the continental groundwater (from the Plateau d'Auge).



Fig. 2 – Destroyed building by the acceleration of January 1982 (Maquaire, 1985)

- A hydrologically-driven activity (relation rainfall-groundwater-displacements).
- Multiple water inputs (2 water tables + impluvium) and complex flows.





Fig. 7 - (A) Conductivity measured in springs, ponds, and drains and (B) water flow measured in natural springs at the Cirque des Graves during the field campaigns of October 2018 and April 2019

	Measurements	October 2018	April 2019
	Number of flowing springs	47	72
Tab. 1 - Compared results from the physicochemical campaigns of October 2018 (low waters) and April 2019 (high waters).	Number of ponds with stagnant water	8	18
	Number of flowing drains	7	11
	Temperature range (in °C)	12.0-20.3	9.3-17.7
	Conductivity range (in µS.cm ⁻¹)	711-1103	693-1602
	pH index range	6.68-8.55	7.19-8.58
	Mean measured flow (I.mn ⁻¹)	2.52	2.59
	Total measured flow (I.mn ⁻¹)	109.75	172.47

Flow dynamics assessment from geophysics



Fig. 8 – ERT (electrical resistivity tomography) profiles from the SISCA geophysical campaign (2008)

waters outcropping downstream the chalk panels (high ionic content);

Shallower piezometric **depth** + more ponds in the eastern part (surficial functioning).

Methodology

characteristics (modified from Sinelle, 1989 and Lissak, 2012)

We used 3 approaches with heterogeneous datasets (old and new) to set the hydrogeological mechanisms :

- **Geomorphological and geological appraisal** (i.e. boreholes and geomorphological features) (*Fig 4A*);
- Hydrological appraisal (i.e. physico-chemical analysis and piezometric chronicles) (Fig 4B);
- **Geophysical appraisal** (i.e. electrical resistivity tomography and self-potential surveys) (*Fig 4C*). (3)



Fig. 4 – Type and spatial distribution of the data used for the (A) morphostructural approach, (B) hydrological approach and (C) geophysical approach. 1. Drilling; 2. Chalk compartment delineation (from Lissak, 2012); 3. Spring ; 4. Pond; 5. Piezometric measurement (single or continuous); 6. Drainage network; 7. SP measurement (2018); 8. ERT profile.

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\bigcirc] 5.60-7.10]] 11.60-13.30]
\bigcirc] 7.10-8.00]] 13.30-15.10]
\bigcirc] 8.00-9.40]] 15.10-17.75]
	Interpreted panels	of chall	k (Lissak. 2012)







- Good correlation between ERT and SP :
 - <u>Central area</u> (*Fig 10A*) :
 - Negative SP anomalies on slope breaks (downward waterflows following slip surfaces) correlated with strongest p values;
 - Positive SP anomalies correlated with springs and water

• SP anomaly = downward flow • SP anomaly = upward flow

- SP anomalies increase from west to east (Fig 9A);
- More infiltration between chalk panels in the west half (negative values);
- Horizontal or upward flow in the east (positive values).
- Validation survey in 2019 confirms the values of 2018.
- General trends curves are fitting (Fig. 9B) despite of few values with a gap over 10mV (local flow changes ?).



Fig. 5 - Thickness variation of the chalk from borehole logs in or nearby the Cirque des Graves and geometry of the identified panels by Lissak, 2012

- Hummocky and complex geomorphology (Fig. 6) which facilitate both water seepage (cracks and fracture porosity) or stagnation (clayey surficial formations, scarps & counter-scarps);
- **Thinner chalk** in the east and west borders, and particularly in the park (eastern extremity), with smaller chalk panels. Chalk is thicker (10-17 m) in the upstream central area (*Fig. 5*).

Fig. 6 – Main geomorphological features encountered in the Cirque des Graves (location given in Fig. 4). (a) Minor scarps and stairs morphology; (b) Main scarp of the cirque (chalk outcrop); (c) Heads (reworked formations) at the foot of the landslide; (d) Mudflows in Oxfordian marls on the coastline; (g) Recent crack on the RD513; (h) Building near a major scarp in the middle of the slide

accumulation (upward waterflows) and lower p clusters (saturation).

- **Eastern area** (*Fig 10B*) :
- Weak resistive thickness in surface (thinner and reworked chalk);
- Strong positive SP anomalies which underlines a parallel or upwards flow (no significant sinking of water).



Fig. 10 - Comparison between the SP survey (2018) and the resistivity gradients from the ERT survey during the SISCA project (2007-2008) at (A) the middle-west part of the Cirque and (B) the east part of the Cirque (park)

- The main discharge from the continental GW is at **the rearmost zone** of the main scarp (*Fig. 9*); (1)Division of the hydrogeological behaviour in three compartments : (2)
- **Eastern part** : shallow waterflow in heterogeneous matrix, parallel flow (undifferentiated GW) ;
- **Central part**: partially splitted flow between chalk and sands GW's, with permeabilities (downward flow identified) and a continental discharge throughout the year (numerous permanent springs);
- Western part: less data but probable deeper functioning (few springs, high scarps, large chalk panels).